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CASE STUDY

Application of life cycle assessment to the production of man-made crystal glass

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Abstract
Background, aim and scope This paper presents a life cycle assessment (LCA) of the manufacturing process of crystal glass products in order to evaluate the potential environmental impacts due to a crystalware company located in Colle di Val d'Elsa, Siena (Italy). Since there is not any published research specifically focussed on crystal production to our knowledge, outcomes from this study would represent a first documented evidence gathered from an LCA of crystal glass products. Once a detailed description of the production process was provided, different categories of impacts were assessed and analysed. Outcomes allowed us to identify 'weak points' in the production process and propose possible solutions for decreasing the risk of negative effects on the environment.
Materials and methods According to the LCA methodology, the whole life cycle of crystal glass was structured into four primary phases—raw materials acquisition, crystal glass manufacturing, product utilisation and final disposal—each of which includes a set of sub-processes. Through an accurate life cycle inventory, primary data, relative to the year 2006, were elaborated through the EDIP database. The calculation of impacts was aided by GaBi4 software with reference to a functional unit corresponding to 1 kg of crystal glass products. Relative to the *CML2001* problem-oriented approach, a set of impact categories was used for the classification and characterisation of the life cycle impact assessment. Potential category indicators were finally accounted for and normalised in accordance with the *CML Western Europe* method.
Results The following ten impact categories were assessed: (1) depletion of abiotic resources, (2) acidification, (3) eutrophication, (4–6) ecotoxicity (marine and freshwater aquatic as well as terrestrial, respectively), (7) climate change (greenhouse effect), (8) human toxicity, (9) stratospheric ozone depletion and (10) photo-oxidant formation. Results showed that among the main phases, crystal glass manufacturing is the one with the highest environmental impact and emissions to air, mainly due to an intensive use of energy and materials. In particular, some sub-processes within the manufacturing stage, such as melting in furnaces, acid polishing, cutting and forming, were found to hold a high responsibility for most of the environmental effects. The main effects depend on CO_2, NO_x and SO_2 emissions, heavy metals emissions and use of non-renewable resources. In particular, the latter is due to the processes of extraction, refining, transport and use of fuels such as natural gas.
Discussion Results were analysed relative to each of the main processes involved in the crystal glass life cycle and critical points were investigated in order to inform the administrators of the crystalware company and address future choices towards a more sustainable production. Some technical solutions were proposed in order to improve environmental performances. Impacts due to the use of lead in the mixture were widely treated in literature and briefly discussed here.

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Conclusions An accurate energy and material flow inventory allowed us to assess the potential environmental impacts of the crystal glass production in Colle Val d'Elsa, including the effects of processes occurring within the industrial plant and those due to the import of products and services from outside. Through the case study, we aimed to provide an exhaustive description of the main steps in the process and clear results relative to different impact categories. Outcomes showed that some procedures could be implemented in order to decrease these impacts. The use of lead is an irreplaceable characteristic of crystal products, but also a critical point to deal with. Nevertheless, the high quality of man-made crystal products makes the use of lead acceptable. The LCA of crystal glass products presented in this paper provided an accurate description of processes and procedures that can mirror a traditional production in a broader sense. This paper can therefore represent a valuable reference for future studies on crystal glass production processes.

Recommendations and perspectives The LCA method was performed for identifying critical aspects in the production process from an energetic and environmental viewpoint and was useful for constructing a model of the crystal glass production in Colle di Val d'Elsa. This can be a starting point for processing an environmental product declaration.

Keywords CML2001 · Crystal glass · Crystalware · Environmental product declaration (EPD) · Lead glass · Life cycle assessment (LCA)

1 Background, aim and scope

In Italy and most of the European countries, eco-efficiency initiatives are primarily based on a voluntary approach (Culaba and Purvis 1999). Companies which implement eco-efficient practices take care of environmental cycles, carefully manage raw materials sources and improve the technical efficiency of their production processes and the quality of their products. Also, they develop long-term policies of environmental as well as economic sustainability and tend to respond to the pressure of the global market by enhancing their reputation and trust (Mata and Costa 2001). The attention of industrial producers to environmental problems is advancing, with the aim of decreasing materials and energy waste and increasing quality of products and services. In particular, crystal glass products have a high environmental concern and should require a more stringent compliance with environmental effects such as toxic emissions to air as well as the discharge of contaminating agents into water reservoirs (Shapilova and Alimova 2000).

The lead crystal industry produces highly designed drinking glasses, stemware, cups, goblets, vases and similar articles. Crystal, or 'lead crystal', is the term used to describe a glass composition with high concentrations of Pb, used for both hand and machine-based production of decorated glass items. Crystal glass contains up to 35% of lead oxide (Lee et al. 1997). An EU directive (EU Directive 69/493/EEC 1969) states definitions and rules for chemical composition, physical and manufacturing characteristics, labelling and other forms of advertising of crystal products and glass traded within the EU. According to this, 'crystal glass' must contain more than 24% PbO (Hynes and Jonson 1997). A moderate addition of PbO into glass increases chemical resistance. A high lead content decreases the melting temperature and results in a lower hardness and a higher refractive index, which determines 'brilliance' (Pfaender 1996). For simplification, this paper presents the terms 'lead glass', 'crystal glass' and 'crystal' synonymously.

The case study presented in this paper describes the life cycle assessment (LCA) of crystal glass products by evaluating the potential environmental impacts due to a well-established crystalware company located in Colle di Val d'Elsa, Siena (Italy). The production system under study is representative of a small-medium company, closer to a handmade enterprise than to a real industrial system, and usually more interested in quality than quantity of products.

2 Goal and scope definition

The scope of this study was to evaluate the potential environmental impacts due to the crystalware company. In particular, the analysis of processes and their effects allowed us to detect 'weak points' in the production process in order to suggest possible solutions for improving environmental performances.

Among these, the use of lead is one of the critical points to deal with, but it is also an irreplaceable characteristic of crystal products. The high quality of man-made crystal products makes the use of lead acceptable. Nevertheless, impacts due to the use of lead, in general, were widely treated in literature and briefly discussed here (see Section 3.1).

Since there is not any published LCA research in the field of crystal production to our knowledge, it was not possible to compare results of our study with previous ones. The life cycle impact assessment (LCIA) of crystal presented here therefore provided an accurate description of processes and procedures of crystal glass production that can be considered as a basis for future evaluations of the life cycle of crystal products in a broader sense. This paper aims to be a reference to address or to compare future studies on crystal glass production processes.

Direct and indirect responsibilities for the potential environmental impacts calculated were identified. Alternative technological solutions to improve the production performances of the company, as well as to reduce environmental costs of consumption and wastes, were provided.

3 Materials and methods

This study focuses on the whole life cycle of crystal glass products 'from cradle to grave'. Technical and organisational aspects of LCA were provided based on the recommendations listed in the ISO 14040 (2006) and 14044 (2006). Based on the observation of procedures and processes in the industrial plant of Colle di Val d'Elsa and considering external products and services, whether they were available in the literature or not, a detailed description of the production process was provided as clearly and exhaustively as possible through a schematic model.

The life cycle was structured into four primary phases, as illustrated in Fig. 1: (1) raw materials acquisition (upstream stage); (2) crystal glass products fabrication (manufacturing stage); (3) product utilisation (use stage) and (4) final disposal (end-of-life stage).

The first stage of raw materials acquisition includes all the activities required for gathering and manufacturing raw materials and fuels. This stage also includes the process of transport of raw materials to the industrial plant.

The second stage includes the production processes that take place within the industrial plant: (a) mixing of raw materials, (b) melting furnace, (c) crystal forming, (d) tempering processes, (e) cutting processes, (f) acid polishing and (g) packing. The manufacturing stage also included 'closed-loop recycling', as described by Klöpffer (1996). This consists of the recovery of crystalware defective pieces from the sub-processes 'c', 'd' and 'e' that, once rejected and scrapped, are reused in the mixing of raw materials without undergoing chemical transformations. Rejected materials are usually huge in quantity due to the high quality of crystal products that imposes one to scrap all the items with a physical defect or refractory impurities after crystal forming or handling. Moreover, in order to avoid the release of impurities described above, refractory clay pots used in the melting furnaces are replaced quarterly. Input and output data for the refractory material production (pot clay) was provided by IPPC (European Commission IPPC (2006b), although its final disposal process was not considered in this study.

The third stage of the analysis focuses on the *use* of the final product and includes transport from the company to the distribution centres (shops for wholesale and retail trade). In this stage, we estimated a 5% loss of crystalware by consumers during use, since high-quality crystal products are usually kept for many years. This crystalware waste (output flow connected with the fourth stage) is much lower than other common glass items (e.g. bottles). As in the first stage, data on transport were estimated by the

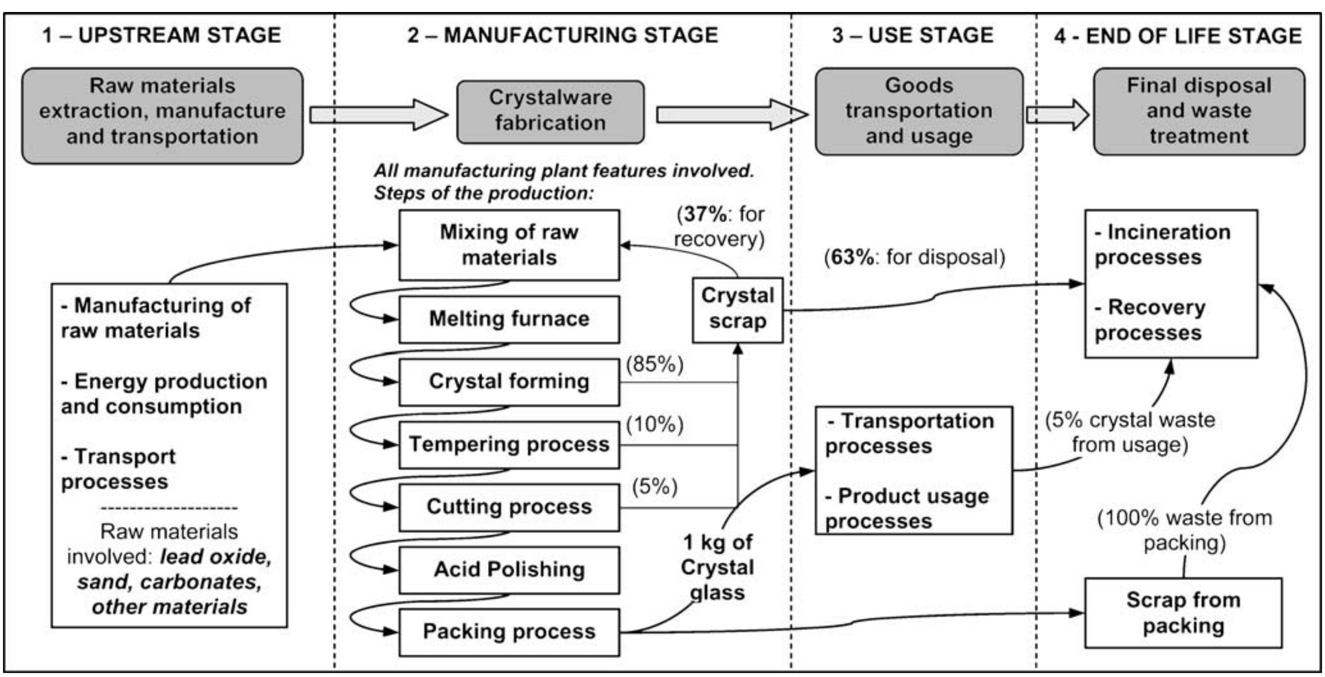

Fig. 1 Life cycle and relative flows diagram of the crystal glass production, with a graphic definition of the system boundary

crystalware company on the basis of the haulage distance given for each load (1 unit of haulage: kg·km).

The fourth stage, or end-of-life phase, was considered based on the assumption that the crystal scrap from the manufacturing and use stages is collected, recovered and incinerated through the same disposal method of non-recyclable, common glass. This generic end-of-life scenario was chosen because of the scarcity of information about crystal disposal. The difficulty of establishing a quantity of crystal discarded after use was also due to the fact that about 22% of the crystal manufactured by the company in Colle Val d'Elsa is sent outside of Italy, in many different world countries. This made it impossible to determine a statistical survey of data about use and waste. Therefore, the end-of-life stage of crystal glass was assessed by considering data from the EDIP database for combustion (i.e. wood), recovery and incineration processes (i.e. lead glass scraps; plastics, polyurethane, paper and cardboard collected from packing) and from META (2000) for landfill processes (i.e. dust bags and lead oxide packages from the manufacturing stage).

Primary data were directly provided by the crystalware company. Energy use was included, focussing on the processes of production and distribution of electricity and combustion of different fossil fuels and natural gas, particularly in the manufacturing stage during which furnaces require a high energy demand. Processes in this phase were developed based on primary data collected in the plant (Table 1). The EDIP database was then used (http://www.lca-center.dk/cms/site.asp?p=728) in order to collect background data. In particular, it provided aggregated outputs for most kinds of power supplies, as well as for secondary processes in raw materials production, transport and disposal in general (Table 2).

Life cycle inventory (LCI) and LCIA were performed through the LCA software GaBi4 with reference to a functional unit corresponding to 1 kg of crystal glass products, packed and ready to be distributed.

Table 1 Company system features (second stage): estimated consumptions

2nd Stage (manufacturing)		Power (kW)	Work (h·day)	Consump. (kWh)
Phases	Machineries			
Mixing of raw materials	Forklift truck[a]	2.40E+01	1.50	3.60E+01
	Shredders	4.50E+00	0.50	2.25E+00
	Mixer	2.30E+01	0.50	1.15E+01
	Scrubber	7.50E+00	8.00	6.00E+01
Melting furnace	Scrubber	7.50E+00	8.00	6.00E+01
	Auger transport	7.50E−01	0.25	1.88E−01
	Electric furnace	4.40E+00	24.00	1.06E+02
	Calcara[b]	3.00E+01	2.00	6.00E+01
	Electric cabinets	1.50E−01	8.00	1.20E+00
	Cooling circuit	6.80E−-02	8.00	5.44E−01
Crystal forming	Blower	1.50E+00	6.00	9.00E+00
	Injection machine	2.20E+00	6.00	1.32E+01
	Centrifuge	1.10E+01	6.00	6.60E+01
	Compressor	5.00E+01	13.00	6.50E+02
	Dryer	1.12E+00	13.00	1.46E+01
Tempering	Temper plant	4.50E+00	13.00	5.85E+01
Packing	Coders	2.00E+00	1.00	2.00E+00
	Polyureth. system	9.20E−01	1.00	9.20E−01
		Estimated consumption rate		
Cutting	Water consump.	0.01 m^3/piece treated		
	Power consump.	0.08 kWh/piece treated		
Polishing	Water consump.	0.03 m^3/piece treated		
		Percent of natural gas usage among the machinery		
Melting furnace	Primary furnaces	60.35		
	Second. furnaces	7.03		
Forming	Flames and furnaces	28.10		
Tempering	Temper plant	4.52		

[a] Consumption estimated for battery lifetime

[b] Typical furnace for melting sand and carbonates

Table 2 Life cycle inventory table

Input types and data referred to 1kg of crystal glass packed (functional unit)				Ref. for outputs
Upstream stage				
Sodium carbonate		–[a]	kg	–[b]
Potassium carbonate		–[a]	kg	–[f]
Lead oxide		–[a]	kg	–[g]
Sand		–[a]	kg	–[b]
Antimony trioxide		–[a]	kg	–[b]
Barium carbonate		–[a]	kg	(European Commission 2006a; Ganapathy 2000)
Sodium antimoniate		–[a]	kg	–[c]
Lithium carbonate		–[a]	kg	–[c]
Potassium nitrate		–[a]	kg	–[c]
Transport processes	By cargo boat	7.14E+02	kg·km	–[b]
	By goods train	2.14E+02	kg·km	–[b]
	By truck	8.37E+02	kg·km	–[b]
Manufacturing stage				
Mixing of raw materials				–[d]
Electric power		7.22E−01	MJ	–[b]
Crystalware scrap (recovered)		36.7	%	–[e]
Melting furnace				
Mixed product		3.55E+00	kg	EMEP/CORINAIR 2006
Refractory material		5.35E-02	kg	European Commission (2006b)
Natural gas		2.05E+00	MJ	–[b]
		3.27E+00	kg	–[b]
Crystal forming				–[d]
Electric power		6.72E+00	MJ	–[b]
Natural gas		1.36E+00	kg	–[b]
Oxygen		1.06E−01	kg	–[b]
Tempering processes				–[d]
Natural gas		1.97E−01	kg	–[b]
Electric power		5.22E−01	MJ	–[b]
Cutting processes				–[d]
Electric power		5.40E−01	MJ	–[b]
Water consumption		1.03E+01	kg	–[b]
Acid Polishing				–[d]
Hydrogen fluoride		1.12E−01	kg	(European Commission 2006a; McCulloch and Lindley 2003)
Sulphuric acid		4.71E−01	kg	–[b]
Water consumption		2.57E+00	kg	–[b]
Natural gas		5.75E−02	kg	–[b]
Electric power		6.04E−01	MJ	–[b]
Packing processes				–[d]
Polyurethane		8.93E−03	kg	–[b]
Pallet (number of pieces)		3.86E−04	Pcs.	–[b]
Cardboard/carton		3.80E−01	kg	–[b]
Plastic		5.70E−02	kg	–[b]
Electric power		4.05E−04	MJ	–[b]
Use stage				
Crystalware packed		1.00E+00	kg	(fun. unit)
Distribution processes	By plane	1.05E+03	kg·km	–[b]
	By truck	7.52E+02	kg·km	–[b]
End-of-life stage				

Table 2 (continued)

Input types and data referred to 1kg of crystal glass packed (functional unit)				Ref. for outputs
Crystal scrap	by consumers	0.05	kg	–[b]
	by manufacturing	1.38E+01	kg	–[b]
Dustbags (in processes 1 and 2)		6.13E-01	kg	(META 2000)
Waste water (in process 6)		2.57E+00	kg	(Lee et al. 1997; Krulik et al. 2003)
Scrap from packing				–[d]
Wood (pallet)		3.28E−03	kg	–[b]
Polyurethane scrap		8.93E−03	kg	–[b]
Paper and board scrap		3.80E+01	kg	–[b]
Plastic scrap		5.70E−02	kg	–[b]

[a] Data for quantity of raw materials used is protected confidentially

[b] Emissions are included as process data from EDIP database

[c] Process not available

[d] New (sub-)process specifically developed for this study. Outputs mostly refer to the aggregated ones from b

[e] Percentage estimated on the total of manufactured crystal scrap

[f] Altair Chimica Spa, 2006 (potassium carbonate manufacturer)

[g] Penox Italia Srl, 2006 (lead oxide manufacturer)

[h] An estimated 5% of crystal waste from usage stage

A list of impact categories and assessment methods was selected from CML2001 (Guinée et al. 2001). The CML2001 method was chosen among other similar methods (e.g. EDIP97) for its characteristics of applicability and completeness, even if it has some limits and biases, mainly in the categories of toxicity-related impact (Dreyer et al. 2003). However, in accordance with the characterisation modelling, the CML2001 method may involve other well-comparable impact categories, such as global warming, acidification or nutrient enrichment. This method was employed in other LCA studies of industrial, energy and manufacturing processes (Bösch et al. 2007; Ribeiro et al. 2007; Strauss et al. 2006).

3.1 Assumptions and limitations

The main assumptions concern data collection and calculation, particularly for processes such as extraction, manufacturing and transport of raw materials. Background data for these processes were collected from inventory tables, databases and other published works. Some of this data were provided directly by the producers.

Data relative to mixing agents, such as potassium nitrate, sodium antimoniate and lithium carbonate, and the processes of their extraction and refining were unavailable. Nevertheless, we demonstrated that mixing agents used in the process provides negligible effects. In fact, assuming that different mixing agents come from similar extractive and refining processes, and even their function is comparable, we found that the same quantity of barium carbonate, a similar stabiliser and/or refining agent, would provide effects corresponding to 0.001% of the total (see Table 2).

In the phases of use and disposal of crystal glass products, we presented a single scenario for the crystal end-of-life stage. Moreover, productions of machineries and plants were neglected (Baldo et al. 2005), and the ‘capital energy’ (the energy needed for the industrial plants building) was not considered. Additionally, the quantity of raw materials used to obtain the crystal glass mixture was given in aggregated form for confidentiality.

Primary data were collected from January 2006 to June 2007, and we can moreover assume that lead glass manufacturing has remained unchanged for decades. Background data (e.g. transport, fuel extraction, refinery and combustion, energy supply and disposal) was taken from the EDIP database that usually refers to previous studies developed in northern Europe from 1997 to 2006; for example, the emissions due to the use of electricity were considered relative to the European electric grid and data on the use of natural gas were elaborated based on the Danish ‘DK Natural Gas’.

The evaluation of environmental issues specifically related to lead was not within the scope of our study. We did not focus our attention specifically to the effects associated with the use of lead, although lead oxide makes up a fundamental share of crystal glass. Nevertheless, for a deeper description of the environmental aspects related to lead processing in industrial activities, we cross-refer to recent outcomes in the literature cited. Relative to the upstream phase, some authors provided a deep analysis of the emissions and environmental effects related to lead-

mining activities (Fthenakis et al. 2008; Higgins et al. 2007). Shapilova and Alimova (2000) highlighted environmental problems due to lead compounds in the processes of crystal glass production and manufacturing. Moreover, in the present research, we assumed that emissions to air of "metals" from crystal glass furnace processes are largely contained in the particulate matter. Sources of metals may be impurities in raw materials and additives used to impart specific properties (e.g. lead oxides, and colourants/decolourants), cullet and fuel. In our case study, these emissions are controlled by the use of dust bags, which are highly efficient dust collection devices. Cutting activities can also give rise to dust emissions, but these are usually controlled by cutting under liquid (water).

Moreover, an evidence of the potential lead intake from crystalware under conditions of consumer use was well exposed by Guadagnino et al. (2000, 2002).

More uncertain aspects are related with the end-of-life phase, although the crystal glass scrap is classified as not being dangerous by the current Italian law (Decreto legislativo Nr. 22 1997), which is in compliance with the latest European law on crystal glass use.[1] The former establishes two ways for the management of crystal scrap outcoming from the factory, which in our case corresponds to about 63% of raw materials once mixed and melted in the manufacturing stage (about 37% of these crystal scraps are recovered in the mixture). In fact, we have estimated a very low (negligible) volume of crystal waste due to consumers' use (see Fig. 1):

1. a redistribution in container and domestic glass wastes where a part of the crystal scrap (we estimated a 50% of the total) may be recovered as cullet for other glass production systems. In fact, once mixed with cullet of common glass or other glass-based materials, the lead concentration drastically decreases to a negligible quantity. This recovery potentiality has been well illustrated by van Santen and Beerkens (2005). They reported that the acceptance limit for heavy metals (mainly lead, together with the less important components: cadmium, mercury and hexavalent chromium) in the packaging glass is 200 ppm.
2. the route of incineration and/or landfill (the other 50% of crystal scrap, we estimated), when the crystal presents too many impurities for being remelted. To calculate emissions in this phase, we considered the same disposal methods for non-recyclable common glass. Although this may be a large approximation, some studies confirm that the main sources of lead destined to incineration plants and/or landfills are electronics, batteries and other materials (e.g. plastics, fishing tools, cathode ray tubes, ceramics, solders, lead flashing, residues from metal shredding, steel reclamation, cable reclamation, etc.), and only a very small percentage is due to crystal glass scraps from man-made industries (Nordic Council of Ministers 2003; Salomone et al. 2005; Andreola et al. 2007).

[1] 2006/690/EC: Commission Decision of 12 October 2006 amending, for the purposes of adapting to technical progress, the Annex to Directive 2002/95/EC of the European Parliament and of the Council as regards exemptions for applications of lead in crystal glass.

4 Results

Results from the LCI were shown in Table 3 for each of the four primary phases. It is shown that most of energy consumption (about 89%) and material use (about 93%) are in the manufacturing stage. This is due primarily to the use of non-renewable energy resources such as crude oil, hard coal, lignite and natural gas. The latter was, in particular, the highest contributor, especially in the two sub-processes of melting in furnaces and forming (about 39% and 16% of the total life cycle energy consumption, respectively).

Most of the material use (about 93%) was due to processes in the manufacturing stage and, in particular, to the water consumption, which was the highest flow accounted (about 64%).

In terms of outputs, the manufacturing stage had the highest values (about 83%), especially due to air, water and soil emissions. The major output flow was the carbon dioxide emitted to air (about 52% of total emissions), mostly detected in the manufacturing stage (about 45%). The sub-process of the melting furnace was, in particular, the major source of CO_2 emissions.

Based on the life cycle inventory, a list of significant effects was completed. Ten potential impact categories (and their characterisation factors) were identified as follows: (1) depletion of abiotic resources (abiotic depletion potential, ADP), (2) acidification (acidification potential, AP), (3) eutrophication (eutrophication potential, EP), (4–6) ecotox-

Table 3 Aggregated results of the life cycle inventory

	TOT. (%)	Stages (%)			
		1	2	3	4
Energy[a] consumption	100	5.41	88.66	6.43	0.39
Materials and resources use[b]	100	4.98	93.30	0.54	2.64
Emissions, wastes, products in output[c]	100	17.45	82.84	6.94	3.78

[a] Highest contributor: *natural gas* (60.89%)

[b] Highest contributor: *water* (64.02%)

[c] Highest contributor: *CO_2* to air (51.66%)

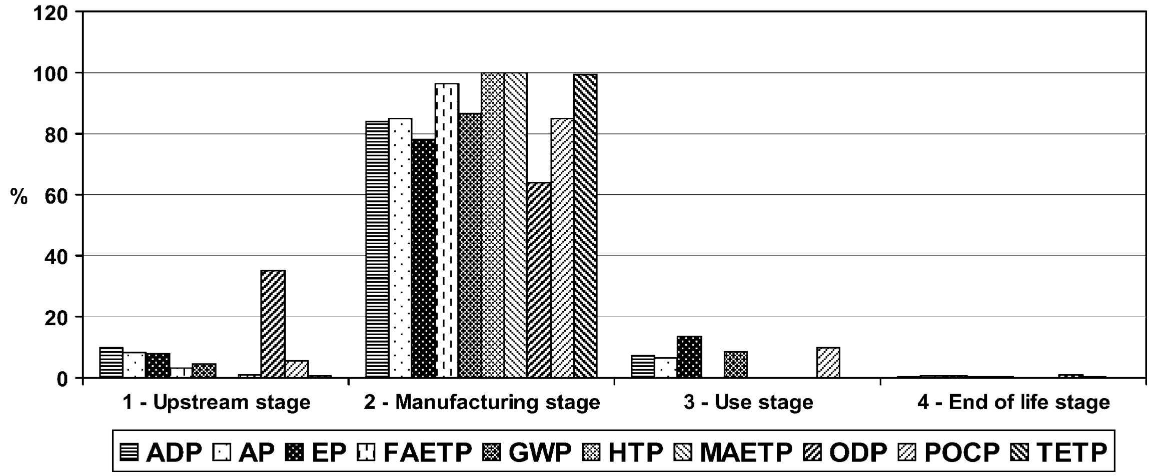

Fig. 2 Results for the characterisation of environmental impacts. The contribution of ten category indicators is considered: (1) abiotic depletion potential (*ADP*); (2) acidification potential (*AP*); (3) eutrophication potential (*EP*); (4–6) marine aquatic, freshwater aquatic and terrestrial ecotoxicity potential (*MAETP*, *FAETP* and *TETP*, respectively; (7) global warming potential (*GWP*); (8) human toxicity potential (*HTP*); (9) ozone layer depletion potential (*ODP*); (10) photochemical ozone creation potential (*POCP*)

icity (marine aquatic, freshwater aquatic and terrestrial ecotoxicity potential; MAETP infinite, FAETP infinite and TETP infinite, respectively), (7) climate change (global warming potential, GWP 100 years), (8) human toxicity (human toxicity potential, HTP infinite), (9) stratospheric ozone depletion (ozone layer depletion potential, ODP steady state) and (10) photo-oxidant formation (photochemical ozone creation potential, POCP).

With regard to the LCIA results, Fig. 2 shows the environmental impact assessment for each stage of the life cycle. The manufacturing stage had the greatest contribution to all the impact categories selected, especially for those regarding ecotoxicity potentials. The other three stages showed a very low percentage of potential effects that look almost negligible compared to manufacturing. In fact, low contributions of ODP, ADP, AP, EP and GWP are distributed among the three stages, mostly in the upstream stage. Absolute values of each category index are described in Table 4.

5 Discussion

5.1 Impact assessment

The normalised results obtained by applying the CML2001 method, considering the *CML Western Europe* factors (Guinée et al. 2001), were represented in Fig. 3; normalised impact scores are expressed as yr.capita, which means the per capita interventions for a given area (in this case *Western Europe*) in a reference year (Guinée et al. 2001). According to this normalisation, the largest contributor to potential environmental problems was marine aquatic ecotoxicity. This was mainly due to emissions of hydrogen

Table 4 Characterised indicator results for each stage of the crystal glass LCA applying the CML2001 method (Guinée et al. 2001)

Impact category	Reference quantity	TOT.	Stages			
			1 Upstream	2 Manufacturing	3 Use	4 End-of-Life
ADP	[kg Sb-Eq.]	1.87E−01	1.83E−02	1.57E−01	1.35E−02	3.98E−04
AP	[kg SO_2-Eq.]	1.29E−01	1.04E−02	1.09E−01	8.25E−03	7.40E−04
EP	[kg Phosphate-Eq.]	9.22E−03	7.11E−04	7.19E−03	1.25E−03	6.44E−05
$FAETP_{\infty}$	[kg DCB-Eq.]	9.95E−02	3.10E−03	9.60E−02	8.54E−05	3.60E−04
$GWP_{100\ years}$	[kg CO_2-Eq.]	2.37E+01	1.12E+00	2.05E+01	2.03E+00	5.57E−02
HTP_{∞}	[kg DCB-Eq.]	1.77E+02	3.73E−02	1.77E+02	1.18E−02	5.28E−03
$MAETP_{\infty}$	[kg DCB-Eq.]	3.78E+03	4.08E+01	3.78E+03	2.24E-04	2.67E+00
$ODP_{steady\ state}$	[kg R11-Eq.]	1.20E−07	4.22E−08	7.68E−08	0.00E+00	1.33E−09
POCP	[kg Ethene-Eq.]	1.22E−02	6.88E−04	1.03E−02	1.18E−03	3.37E−05
$TETP_{\infty}$	[kg DCB-Eq.]	8.63E−01	5.01E−03	8.58E−01	9.73E−06	2.98E−04

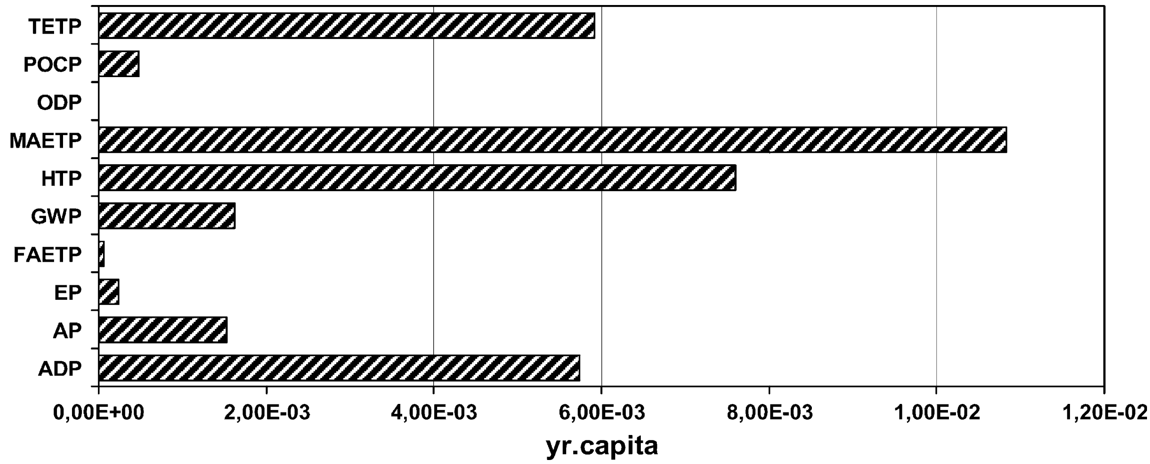

Fig. 3 Normalised impact scores for the crystal glass LCIA applying the CML2001 method [West Europe 1995 (Guineé et al. 2001)]. The normalisation is applied on the category indicators selected for the characterisation of environmental impacts: (1) abiotic depletion potential (*ADP*); (2) acidification potential (*AP*); (3) eutrophication potential (*EP*); (4–6) marine aquatic, freshwater aquatic and terrestrial ecotoxicity potential (*MAETP*, *FAETP* and *TETP*, respectively; (7) global warming potential (*GWP*); (8) human toxicity potential (*HTP*); (9) ozone layer depletion potential (*ODP*); (10) photochemical ozone creation potential (*POCP*)

fluoride during the acid polishing process in the manufacturing phase. Since one would not expect that 'crystal' production is a relatively marine toxic activity, Heijungs et al. (2007) discussed this point and described solutions for identifying and avoiding a possible mistake in the normalisation when CML method is applied.

Moreover, human toxicity potential, mainly due to heavy metal emissions in the melting process, was higher than other indicators such as global warming, acidification, eutrophication, terrestrial ecotoxicity (heavy metals in the air during the melting process) and abiotic resource depletion (the use of natural gas in the process of melting and forming).

Since the manufacturing stage achieves the highest level of environmental effects compared to the other three stages, it was described in detail in order to identify 'weak points' in the production process relative to each category of impact. A list of sub-processes and weak points in the manufacturing phase is provided in Table 5.

It was difficult, however, to evaluate the relative size of the potential impacts calculated because it was not possible to compare indices and effects with any previous study. Furthermore, the values of equivalent kilograms obtained from the characterisation, with particular reference to CO_2 equivalent kilograms, are not easily comparable with the threshold values stated in the national allocation plan for greenhouse gas emissions.[2] In fact, the level of production for the crystalware company examined is not high enough to undergo legislative restrictions that are clearly different from other larger crystalware companies. An Italian Ministerial Decree exists[3] that sets a minimum production limit, beyond which industries must declare the amount of CO_2-equiv. emitted. Therefore, it was not necessary to assess the actual type and quantity of substances emitted during the life cycle of crystal glass since the production of this company is less than 20 tonnes/day, as stated in this decree.

Nevertheless, outcomes from this study were helpful to crystalware producers in Colle Val d'Elsa in order to determine critical processes that need more attention. Some of these, such as melting in furnaces and acid polishing, directly depend on the crystalware company. Due to this direct responsibility, the company could make interventions to reduce emissions and/or consumption. For instance, once a high impact due to fossil fuel use was detected, we suggested developing a technology for heat recovering from furnaces that would strikingly reduce the energy demand within the industrial plant and the emissions to air due to fuels combustion.

However, for a process such as mixing, which presented the highest exploitation of non-renewable resources (e.g. mineral resources), we highlighted an indirect responsibility of the company, since consumption during extraction and manufacturing of raw materials occurs out of the company's control. The problem of direct and indirect burdens is an important point, especially because the Community

[2] Actuation of directive 2003/87/EC and 2004/101/CE of the European Parliament and of the Council establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC. Schema di Piano Nazionale d'Assegnazione per il periodo 2008–2012 elaborato ai sensi dell'articolo 8, comma 2, del D.lgs. 4 aprile 2006, Nr. 216.

[3] Decreto Ministeriale Nr. 96 (2006), sul rilascio del riconoscimento dell'attività di verifica delle comunicazioni delle emissioni prevista dall'articolo Nr.15 della direttiva 2003/87/CE e dall'articolo Nr.4, comma 6, del decreto DEC/RAS/074/2006.

Table 5 Results of characterisation: manufacturing *weak points* list

Charact. factor	Weak points (sub-processes)	Relative contrib. (%)	Charact. result	Ref. quantity
ADP	Melting	45.26	8.47E−02	[kg Sb-Eq.]
	Forming	18.62	3.49E−02	
AP	Melting	17.55	2.26E−02	[kg SO_2-Eq.]
	Cutting	17.23	2.22E−02	
	Polishing	39.23	5.05E−02	
EP	Melting	41.27	3.80E−03	[kg Phos.-Eq.]
	Forming	12.78	1.18E−03	
$FAETP_{\infty}$	Melting	67.27	6.69E−02	[kg DCB-Eq.]
	Cutting	12.67	1.26E−02	
	Polishing	11.64	1.16E−02	
$GWP_{100\ yr}$	Melting	43.45	1.03E+01	[kg CO_2-Eq.]
	Forming	17.54	4.16E+00	
	Cutting	10.05	2.38E+00	
HTP_{∞}	Melting	99.64	1.77E+02	[kg DCB-Eq.]
$MAETP_{\infty}$	Melting	40.48	1.53E+03	[kg DCB-Eq.]
	Polishing	53.89	2.04E+03	
$ODP_{st.\ state}$	Polishing	56.04	6.74E−08	[kg R11-Eq.]
POCP	Melting	33.37	4.06E−03	[kg Ethene-Eq.]
	Forming	13.95	1.70E−03	
	Polishing	22.62	2.75E−03	
$TETP_{\infty}$	Melting	97.22	8.39E−01	[kg DCB-Eq.]

Policy is heading towards a way of assigning responsibility for carbon dioxide (and other greenhouse gas) emissions. Allocating emissions may allow us to better understand which processes provide the highest emissions and to define who releases what (Ridolfi et al. 2008; Bastianoni et al. 2004; van Asselt and Biermann 2007).

5.2 Interpretation

Manufacturing had the greatest contribution to all the potential environmental impacts selected (see Table 4 and Fig. 2). The most significant effects in the case study were: greenhouse gas emissions, emissions of nitrogen oxides and sulphur dioxide, emissions of heavy metals and use of non-renewable resources such as natural gas. Extraction, refining and use of natural gas inevitably cause a release of hazardous substances into the environment.

In the manufacturing stage, the melting sub-process was found to hold more responsibility for environmental effects. The processes of forming, cutting and polishing are also responsible for most of the emissions. In fact, they were all phases of crystal processing that required the use of industrial technologies. Furnaces for melting raw material mixtures in the industrial plant need to be continuously (24 h) kept at a high temperature of 1,200/1,300°C. However, technological improvements would have positive effects for saving energy; for example, heat recovery furnaces would enable energy internal recycling or renewable energy resources, such as biofuels, would represent an alternative to the use of natural gas. Moreover, a number of electrically heated furnaces are used in the glass industry sector, but there is an upper limit to economic viability (European Commission 2001).

The replacement of natural gas, theoretically, may allow a net reduction of emissions from combustion to feed furnaces directly and from the extraction, refining and distribution processes of natural gas indirectly. Nevertheless, despite high emissions, the need of continuous processes in high temperature furnaces and raw materials acquisition cannot be easily modified if we want to guarantee the production of high-quality hand-crafted products based on such a traditional method of manufacturing.

Furthermore, techniques could be implemented for reducing the potential impacts of water processes, which is one of the most used resources during the manufacturing of crystal. In some cases, in fact, wastewaters contain environmental pollutants, mainly as a result of the polishing process. This highlights the importance of ensuring an accurate water treatment before releasing to the environment. As stated by Zhernovaya and Onishchuk (2003, 2005), procedures are needed to precipitate the hazardous compounds.

An optimum environmental and technological solution for the utilisation of waste generated by chemical polishing of crystal products is to separate the lead-bearing precipitate from the polishing sewage, with subsequent conditioning for each component. Treatment of the lead-bearing precipitate from the chemical polishing waste using a sodium carbonate alkaline solution yields the compound $NaPb_2(CO_3)_2(OH)$, a compound called 'CLM' (complex of the lead-bearing material). This may be reused as raw material in a good mixture of glass decoration from low flux (Zhernovaya and Onishchuk 2003, 2005). Improvements in the cleaning of hazardous waste generated by the crystal glass polishing were also performed (Lee et al. 1997), suggesting methods to Korean glass industries systems for reducing the wastewater in treatment facilities and water consumption as well as the establishment of a zero-discharge system. It is important that the wastewater discharge from the acid-polishing processes be fully processed and purified.

Improved environmental and technical performances of the crystalware company, with respect to potential environmental impacts, would reflect an increase in product quality rather than quantity. Thus, the application of the LCA to the crystal products may be a useful tool for a crystalware company to understand and improve procedures, which are hardly comparable with the production of common glass. In fact, crystal and glass represent two different ways of manufacturing: on the one hand, high quality, high cost and high artistic value and on the other hand, low cost, high versatility and high reutilisation.

Moreover, lead glass waste from the manufacturing sub-processes (melting, forming and tempering) could be appropriately recycled as input materials in the mixture of common glass. This would decrease the concentration of lead oxide in glass products and improve the quality of glass itself in terms of brilliance and resistance. Furthermore, lead oxide can be partially or totally replaced by barium, zinc or potassium oxides (European Commission 2001), but at the expense of brilliance and density of crystal glass products.

6 Conclusions

This paper presented a complete life cycle assessment of crystal glass production considering all the main phases from raw materials acquisition and crystal glass manufacturing to product utilisation and final disposal. More in detail, processes included in each stage were analysed in order to exhaustively represent working procedures, considering those occurring within the company and those that are processed outside. This enabled us to provide a detailed inventory table and to assess potential environmental impacts.

The LCA was therefore performed for identifying 'weak points' in the production process from an energetic and an environmental viewpoint. Impacts of high emissions due to the consumption of natural gas were specifically highlighted as a critical point, particularly in the melting process during the manufacturing stage.

This study informed the administrators of the crystalware company in order to plan future actions, such as applying technical improvements in the production process, and to evaluate potential effects by updating data and integrating results of the analysis. For example, it was found that a technology for heat recovering from furnaces would strikingly reduce the energy demand within the industrial plant and the emissions to air due to fuels combustion.

Furthermore, the LCA of crystal glass was made with the aim of developing an environmental standard for the man-made high-quality crystal glass products, such as an environmental product declaration.

The use of up to 24% of lead oxide in the mixture of different raw materials for making crystal glass is a critical point, which needs a more in-depth investigation. Even though an entire life cycle assessment of lead (oxide) could probably be done for evaluating the actual effects on environmental and human health, which was not within the scope of our study. Since lead oxide percentages in crystal glass cannot be modified by law, we assumed that the production of high-quality hand-crafted products makes the use of lead acceptable under the condition that producers plan an accurate management of crystal wastes from the industrial plant.

The LCA presented here can actually contribute to the definition of an environmental profile of the crystal manufacturing and processing. The variability of producing brilliant glasses is very high due to small differences in the production technique and in raw material inputs used. In future works, data on secondary processes, such as those involved in the crystal end-of-life stage, could be refined and more deeply investigated.

In this paper, processes referred to a traditional and common procedure for producing man-made crystal glass. Outcomes probably represent a first documented evidence gathered from an LCA of crystal glass products. This could be a reference study for future works worldwide.

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